NAIC-ID(RS)T-0221-95

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DESIGN AND IMPLEMENTATION OF REAL-TIME POSITION
DIFFERENTIAL GPS

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HUMAN TRANSLATION

NAIC-ID(RS)T-0221-95 6 November 1995

MICROFICHE NR: 95C000690

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English pages: 13

Source: Shishi Wei Zhi Cha Fen GPS De She Ji Yu Shi Jian
Journal of Northwestern Polytechnical University
Vol. 12, No. 3; pp. 354-359

Country of origin: China
Translated by: SCITRAN
F33657-84-D-0165
Requester: NAIC/TASS/Scott D. Feairheller
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A design and implementation method for real time position differential GPS (Global Positioning System) is discussing in this paper.

The differential GPS (DGPS) scheme adopted in this system differs from pseudorange DGPS mainly in that reference stations broadcast position corrections--instead of pseudorange corrections--needed for real time user data processing. This system has the following main advantages: high positioning accuracy, fast corrections, good integrity, simple equipment, and easy operation. In the system, reference stations can delete manually an unsound satellite, and users can choose automatically those satellites selected by the reference stations, so that not only the differential positioning accuracy can be ensured, but also the integrity be improved.

In the paper, the positioning error of position DGPS is analyzed and the experimental results are given. From the theoretical analysis and the experimental results, we can see that the positioning accuracy of this DGPS is much higher than that of GPS. Its static positioning error can reach (2-5)m. Its dynamic features are also excellent.

Key Words Differential GPS (DGPS), Positioning error

* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

Global positioning system (GPS) supplies two types of precision services. The first is precision positioning service (PPS). It utilizes P code (or Y code). It is only used to supply military agencies of the U.S. and its allies. The second is standard positioning service (SPS). It utilizes C/A code and is released to the whole world. In order to benefit itself, the U.S. has adopted selective access (SA) facilities, artificially lowering SPS accuracy. When there is SA, SPS horizontal errors are 100m (2dRMS). Vertical errors are 156m (2σ).

With regard to application realms such as aircraft approach and landing, harbor vessel navigation, precision positioning of vehicles, missile orbit measurements, pilotless aircraft navigation and flight control, and so on--whether or not there are SA influences--SPS accuracies are not able to satisfy requirements at all. Opting for the use of differential techniques to raise SPS positioning accuracies has been a subject of research competition between various nations of the world in the last few years. Differential GPS (DGPS) will not damage U.S. advantages. The U.S. has no need to or any way to limit DGPS research and applications. It is generally believed that the global satellite navigation system (GNSS) will gradually replace other wireless navigation systems. The U.S. space navigation radio technology committee (RTCA), in a report on realizing this type of transition, explained the necessity of differential technology [1]. On the foundation of position differential GPS error analysis, this article puts forward design plans for this type of system. With regard to position differentials, it is necessary that reference stations and users opt for the use of the same satellites. The designed reference stations and user software successfully resolve this problem, not only guaranteeing differential positioning accuracy but also improving system integrity. The systems in question are particularly suitable to accurate navigation of such dynamic users as aircraft, ships, vehicles, and so on.

1 OVERALL DESIGN

1.1 Differential Mode Selection

According to correction amount types, data transmission direction, and processing point, it is possible to divide DGPS modes into 4 types: (1) reference station broadcast false/355 distance correction amount, user processed data; (2) reference station broadcast position correction amount, user processed data; (3) pseudo range data transmited from the user to the

reference station, reference station processed data; (4) position data transmitted from the user to the reference station, reference station processed data. With regard to multiple users, in the cases of modes (3) and (4), reference stations need to use large model high speed computers. Moreover, there is a limit on the number of users. If users require real time positioning data, then, they also require a data up link. In this way, they not only make equipment complicated; moreover, they add problems for user electromagnetic compatibility. The systems which have been developed have been primarily applied to aircraft approach and landing, harbor vessel navigation, precision vehicle positioning, pilotless aircraft navigation and flight control, and so on. In these applications, there is a need for real time positioning data for multiple dynamic users in all cases. Obvicusly, the latter two modes cannot be adopted.

As far as the first type of method is concerned, reference stations broadcast pseudo range correction amounts, and users process data. At different times, the number of satellites visible to reference stations is different. The number of correction amounts which must be sent for pseudo ranges and their rates of change are different. In this way, the time to transmit a frame correction amount is different. According to the recommendations [2] of the U.S. maritime transport radio technique committee (RTCM)'s specialized committee 104 with regard to differential GPS, reference stations make use of 16 types of electrical messages.

The first type of electrical message is correction amounts associated with pseudo ranges as well as their rates of change. When there are 4, 7, and 11 visible satellites, the average time periods required to transmit a frame electrical message are respectively 6.23s, 10.22s, and 16.11s. This type of differential signal form is complicated. Frame length is relatively long. Moreover, it is not constant.

The second type of differential method is reference station broadcast position correction amounts and user processed data. Differential data forms associated with this type of method are simple. Frame length is short and constant. Differential corrections are fast. In order to guarantee differential position accuracy, user satellite selection should be in line with reference station satellite selection. In the case of automatic user software to control satellite selection, which has been developed, it is possible to make user satellite selection and reference station satellite selection the same. Reference station manual control satellite selection software is capable of deleting unsound satellites. These two softwares not only guarantee differential positioning accuracy. Moreover, they improve system integrity.

1.2 System Hardware

The systems in question are composed of two portions--reference stations and users. The number of users is unlimited. Differential data links opt for the use of domestically produced vehicle borne models of U wave band radio telephones. Use of FSK-FM modulation methods is adopted.

Reference stations are composed of TANS II model GPS receivers, antennas, as well as their preamplifiers, RS422/RS232 port switching devices, data link transmiters and antennas, FSK modulation devices, and easily carried USER 386 model micro computers. Computers take GPS receiver outputed measurement values associated with position parameters and the actual values associated with reference station position parameters and continuously carries out comparisions, obtaining position correction amounts. In conjunction with this, in accordance with set data forms, differential data is produced. The data in question goes through FSK modulation devices and is sent to data link transmiters.

Users are composed of TANS II model GPS receivers, antennas, as well as their preamplifiers, RS422/RS232 port switching devices, data link receivers and antennas, FSK demodulation devices, and easily carried USER 386 model micro computers (a single chip computer has already been developed to successfully replace the computers in question). Computers take direct positioning parameters outputed by GPS receivers and data link receiver outputed differential data and carry out processing to obtain user position data after correction. Computers control GPS receivers, making them select the same satellites as reference stations.

1.3 Differential Signal Characteristics

Differential data opt for the use of a spacial rectangular coordinate system or a geocoordinate system and constant frame length. Frames contain: frame synchronicity characters, t, $\triangle x$, $\triangle y$, $\triangle z$, and satellite numbers or are frame synchronicity characters, t, $\triangle Lo$, $\triangle La$, $\triangle Al$, and satellite numbers. They are also capable of sending speed correction amounts. If it is desired to construct differential nets, it is also required to increase reference station indices.

1.4 System Software

System software includes reference station software, user software, and data processing software.

The primary functions of reference station operating software include: input of actual reference station position parameter values; deletion of unsound satellites; pick up from receivers of times, positions, speeds, operating modes, satellite numbers selected for use, and geometrical precision parameters; calculation of position correction amounts; and, in conjunction with this, the production of differential data frame signals in accordance with set data forms and the sending of them to data link transmiters; displaying relevent parameters; and generating data documents requiring storage.

The primary functions of user operating software include: pick up from GPS receivers of times, positions, speeds, operating modes, satellite numbers selected for use, and geometrical precision parameters; pick up from data link receivers of position correction amounts, reference station selected satellite numbers, and differential data aging; calculation of user /356 position parameters after differential correction (It is possible to use spacial rectangular coordinated systems, geocoordinate systems, or polar coordinate systems taking reference stations as origin points for displays); automatic control of GPS receivers to make satellites selected by them and reference stations the same; display of relevent parameters; and, the generation of data documents requiring storage.

Data processing software is used in processing after the fact. The main functions include carrying out coordinate conversions on original data, calculating and graphing, obtaining mean values for various parameters, absolute errors, standard deviations and maximum residual deviations, as well as drawing up

various parameter curves and user courses.

2 ERROR ANALYSIS

2.1 GPS Positioning Solutions

In spacial rectangular coordinate systems, user position solutions can be explained with the use of Fig.1. Si is the ith satellite. x_{si}, y_{si}, z_{si} are the coordinate components associated with Si . rai is the distance vector from the center of the earth to Si . U is the user. x, y, and z are coordinate components associated with U. r is the distance vector from the center of the earth to user U. ri is the distance vector from the user to Si . The direction cosines are e_{ix}, e_{iy}, e_{iz} . The relationship of the three vectors is as below.

(1)

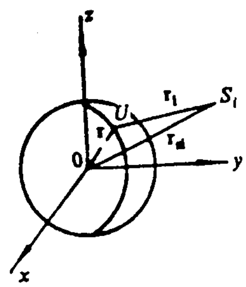

Fig.1 Positioning Solution Graph

ri is the distance from the user to Si . It is the pattern for ri .

The pseudo range measured by receivers from the user to Si is . Then,

$$p_i = r_i + l_u + l_{si},$$

(2)

In the equations, lu is the distance corresponding to user clock error. lsi is the distance corresponding to Si .

$e_i = \mathbf{r}_i / r_i$ is the unit vector from the user to Si . Multiplying both sides of equation (1) by ei , and, in conjunction with this, taking equation (2) and substituting in, one gets

$$\mathbf{e}_i\mathbf{r} - l_u = \mathbf{e}_i\mathbf{r}_{si} + l_{si} - p_i \tag{3}$$

When i= 1-4, it is possible to take the equations above and write them to be the matrix forms

$$\begin{bmatrix} \mathbf{e}_{1x} & \mathbf{e}_{1y} & \mathbf{e}_{1z} & 1 \\ \mathbf{e}_{2x} & \mathbf{e}_{2y} & \mathbf{e}_{2z} & 1 \\ \mathbf{e}_{3x} & \mathbf{e}_{3y} & \mathbf{e}_{3z} & 1 \\ \mathbf{e}_{4x} & \mathbf{e}_{4y} & \mathbf{e}_{4z} & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ -l_u \end{bmatrix} = \begin{bmatrix} E_1 & 0 & 0 & 0 \\ 0 & E_2 & 0 & 0 \\ 0 & 0 & E_3 & 0 \\ 0 & 0 & 0 & E_4 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} - \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{bmatrix} \tag{4}$$

In the equations $E_i = [\mathbf{e}_{ix}\ \mathbf{e}_{iy}\ \mathbf{e}_{iz}\ 1]^T$, $S_i = [x_{si}\ y_{si}\ z_{si}\ l_{si}]^T$

Make $U = [x\ y\ z\ -l_u]^T$ be the user status array.

$S = [S_1 S_2 S_3 S_4]^T$ is the satellite status array.

$P = [p_1\ p_2\ p_3\ p_4]^T$ is the pseudo range array.

$$G = \begin{bmatrix} \mathbf{e}_{1x} & \mathbf{e}_{1y} & \mathbf{e}_{1z} & 1 \\ \mathbf{e}_{2x} & \mathbf{e}_{2y} & \mathbf{e}_{2z} & 1 \\ \mathbf{e}_{3x} & \mathbf{e}_{3y} & \mathbf{e}_{3z} & 1 \\ \mathbf{e}_{4x} & \mathbf{e}_{4y} & \mathbf{e}_{4z} & 1 \end{bmatrix}$$ is a 4x4 geometrical matrix

$$A = \begin{bmatrix} E_1 & 0 & 0 & 0 \\ 0 & E_2 & 0 & 0 \\ 0 & 0 & E_3 & 0 \\ 0 & 0 & 0 & E_4 \end{bmatrix}$$ is a 4x16 geometrical matrix

In both cases, what G and A represent are the geometrical relationships between users and satellites. Equation (4) can be simplified to be GU=AS-P. Then,

$$U = G^{-1}[AS - P] \tag{5}$$

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2.2 GPS Positioning Error

When users position directly, errors exist in all the various matrices in equation (5). According to the micro error criterion in error transmission formulae, the errors in matrices G and A can be ignored. Then, GPS direct positioning errors are

$$\triangle U = G^{-1}[A\triangle S - \triangle P] \tag{6}$$

In the equation: delta S is the satellite status error array. It includes satellite clock errors, ephereris errors, and selective access errors (SA). Delta P is the pseudo range error array. It includes measurement errors given rise to by ionospheric effects and tropospheric effects, measurement errors

given rise to by receiver noise and channels, as well as by errors given rise to by various effects.

Equation (6) clearly shows that GPS positioning accuracies are closely related to G. The smaller geometric precision coefficient GDOP values are, the higher positioning accuracies are.

2.3 Position Differential GPS Errors

Real time position differential GPS, which has been developed, takes reference station position parameter measurement values Ur , received by GPS receivers, and actual reference station position parameter values and subtracts them from each other, obtaining position differential correction amounts $\triangle U_r = U_r - U_{r0}$.

. Reference stations broadcast the correction amounts in question. Differential users take position parameters Ud received by GPS receivers and delta Ur and subtract them from each other, obtaining user position parameters after differential correction $U_{dc} = U_d - \triangle U_r$. .

Assuming Ud0 is the true value of user position parameters, then position differential positioning errors

(7)

In the equations: $\triangle U_d = U_d - U_{d0}$ is the user position error when there is no differential correction. Taking equation (6) and substituting into the equations above, it is possible to obtain

$$\begin{aligned}\triangle U_{dc} &= G_d^{-1}[A_d \triangle S_d - \triangle P_d] - G_r^{-1}[A_r \triangle S_r - \triangle P_r] \\ &= G_d^{-1} A_d \triangle S_d - G_d^{-1} \triangle P_d - G_r^{-1} A_r \triangle S_r + G_r^{-1} \triangle P_r\end{aligned} \quad (8)$$

When users and reference stations select for use the same satellites, $\triangle S_d = \triangle S_r = \triangle S$. Because the distances between users and reference stations are much smaller compared to the distances between them and satellites, therefore, $G_d \approx G_r \approx G$, $A_d \approx A_r \approx A$, . The first and third terms of equation (8) cancel each other out, that is,

$$\triangle U_d = G^{-1}(\triangle P_r - \triangle P_d) \quad (9)$$

Table 1 Positioning Error Estimates

	GPS (m)	DGPS (m)	
		185 km	926 km
1星钟误差	3.1	0	0
2星历误差	2.8	0.1	0.5
3SA 误差	28	0	0
4电离层传播误差	9.1	2.2	4.9
5对流层传播误差	1.8	0.6	0.9
6接收机噪声误差	3.1	3.1	3.1
7接收机通道误差	0.6	0.6	0.6
8多路径误差	3.1	3.1	3.1
UERE	30	5.0	6.7
9水平定位误差	45	7.5	10
10垂直定位误差	75	12	17

(1) Star Clock Error (2) Ephereris Error (3) SA Error (4) Ionosphere Propogation Error (5) Troposphere Propogation Error (6) Receiver Noise Error (7) Receiver Channel Error (8) Multiple Path Error (9) Horizontal Positioning Error (10) Vertical Positioning Error

In the equations above, $\triangle P_r$ and $\triangle P_d$ are, respectively, pseudo range measurement errors associated with reference stations and users. They include inonosphere effects, troposphere effects, receiver noise, and distance measurement errors given rise to by receiver channels as well as multiple path effects. When users and reference stations are 500km away from each other on the ground, the included angles for satellites and lines connecting the two are not larger than 1.5°. At this time, user and reference station pseudo range measurement errors given rise to by ionosphere effects and troposphere effects are close to each other. GPS and DGPS positioning accuracy estimates are shown in Table 1 [3-4]. In the table, various errors are all displayed using standard deviations. UERE is user equivalent range error. Horizontal error horizontal accuracy coefficient HDOP=1.5. Vertical error vertical accuracy coefficient VDOP=2.5. 185km and 926km are the distances between users and reference stations.

3 EXPERIMENTAL MEASUREMENT RESULTS

On 12 November, 1992, at a national standardization measurement point, static measurement and dynamic measurement tests were carried out on the systems in question. The coordinate systems opted for the use of spacial rectangular coordinate system WGS-84. Measurement point x, y, and z errors were not greater than 6mm. Measurement results clearly show that the positioning accuracies of the systems in question were an order of magnitude higher than GPS direct positioning accuracies. Static positioning errors are (2-5)m. In GPS/digital map composite systems developed by the author, option has already been made for this type of differential technique. During vehicle mounted tests, vehicle speeds were (20-100)km/h. On digital maps, displayed automotive vehicle positions were always on given routes. Experimental results clearly show that system dynamic performance is good. Table 2 and Fig.2 are experimental results for one point among them. In the table, starting and stopping times are GPS times.

Table 2 Experimental Results

1 测试日期	1992.11.12
2 起始时间	364 023 s
3 终止时间	364 554 s
4 时间间隔	531 s
5 数据总数	623 个

	6 绝对误差 m		7 标准偏差 m	
	GPS	DGPS	GPS	DGPS
x	−9.062	−0.451	10.369	2.619
y	−6.580	−0.880	18.882	3.296
z	43.092	1.262	27.499	5.760
8 水平	32.902	1.463	24.758	3.841
9 垂直	22.558	0.156	22.878	5.606

(1) Test Measurement Date (2) Start Time (3) Stop Time (4) Time Interval (5) Total Data Number 623 Items (6) Absolute Error (7) Standard Error (8) Horizontal (9) Vertical

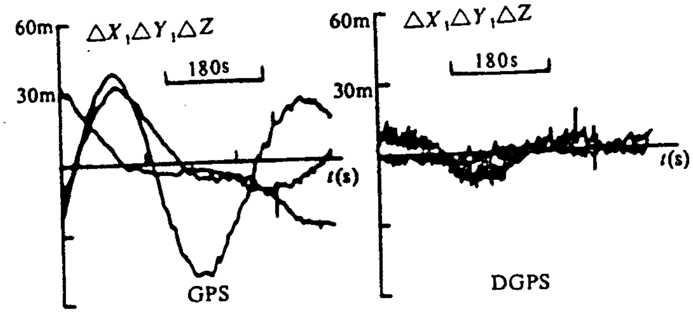

Fig.2 Test Measurement Results

4 CONCLUSIONS

From error analysis and the results of test measurements, it can be seen that, if one wants to get good position differential results, systems should satisfy three points of requirement: (1) reference stations should select for use optimal constellations, getting minimal GDOP values; (2) users should select for use the same satellites as reference stations; (3) when distances between users and reference stations increase, differential positioning errors also increase. When distances between the two are smaller than 500km, location differential positioning accuracies can be raised an order of magnitude compared to GPS direct positions. Besides this, if receiver noise passes through filters, opting for the use of dual path suppression antennas, differential effects are, then, even more obvious.

The real time location differential global positioning system in question possesses the characteristics described below. Position accuracies associated with this system are higher than direct GPS positioning by an order of magnitude. Static positioning errors are (2-5)m. Vehicle borne experiments clearly show that system dynamic characteristics are good. Differential data forms are simple. Frame lengths are short and constant. Differential correction speeds are fast. Differential data goes through smoothing processing, increasing positioning accuracies. Reference stations are capable of manually deleting unsound satllites. Users are capable of automatically selecting the same satellites as reference stations, thus guaranteeing differential positioning accuracy. In conjunction with this, system integrity

is improved. Data links are capable of utilizing ordinary radio telephones. Option is made for FSK-FM modulation. Antijamming capabilities are strong. Software development characteristics are good. Volumes are small. They are light weight. Costs are low. Software design characteristics are good. Operations are reliable. Operating is convenient. Reference station structures are light and handy. Installation and maintenance are convenient.. The introduction into practical coordinate systems is easy. The use of field reference stations is convenient (for instance, pilotless aircraft monitoring and control stations). These systems can be used in the precision navigation of such dynamic users as aircraft, ships, vehicles, and so on. It is also possible to use them in precision positioning of such static users as oil field well drilling.

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